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Systems Engineering Graduate Research as Part of Curriculum – Summary of Research

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Abstract

In this paper, we review and analyze the systems engineering graduate research projects that students have completed as part of their curriculum requirement. The information presented here is gathered over five years. The semester long projects are completed as part of the graduate course titled 'System Development Workshop' taught at Southern Polytechnic State University (SPSU). Students are required to investigate a discipline-related topic in systems engineering in the form of capstone project. The general intent of the project is to give students an opportunity towards the end of their Master's degree courses, to demonstrate and apply the knowledge they have acquired over the course of the curriculum. The work performed in the project draws upon skills and knowledge acquired in the program. Students are required to identify an engineering problem, often in their work environment, and use systems engineering methods to achieve a solution to the problem. At the end of the study, each student prepares a formal report describing the work performed, resulting conclusions and recommendations. In addition, students present their results to the online audience. Students are expected to meet professional engineering standards in their work and reports. The results of the projects are considered for submission to an academic conference or journal in the field. This course gives students, often times their first, taste of research.
The intent of this paper is to demonstrate several examples of research projects completed by students and to investigate the efficacy of a research based course in Systems Engineering graduate curriculum.

Keywords: Graduate Research Course; Systems Engineering Principles; Tools and Techniques

1. Introduction and Background

System development workshop (SYE 6055) is taught as a workshop course for graduate students in systems engineering at the Southern Polytechnic State University. The workshop requires students to investigate a discipline-related topic in systems engineering in a form of a capstone project. The general intent of the project is to

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demonstrate the students' knowledge of the integrative aspects of systems engineering process. The generic systems engineering technical processes are covered in the course so that they can be applied to a variety of research topics chosen by students. This course is usually taken by students towards the end of their two year Master's degree program. The work performed in the project draws upon skills and knowledge acquired in the program.

Students are required to identify an engineering problem, often in their work environment, and then use systems engineering methods to achieve a solution to the problem. At the end of the study, each student prepares a formal report describing the work performed, resulting conclusions and recommendations. In addition, students prepare a presentation for the faculty to discuss their projects and its results. Students are expected to meet professional engineering standards in their work and reports (e.g. INCOSE Standards). Depending on the quality of the work performed, the final paper is considered for submission to an academic conference or journal in the field. This exercise is usually the first experience that graduate students have with writing a technical paper in systems engineering. Students are often surprised by the challenge of choosing an appropriate research topic, literature review, and the general level of rigor required in writing a research paper. In this paper, the process of conducting a graduate research workshop is explained in detail, sample student projects are highlighted and some success stories are celebrated.

The key role of the course instructor is not only to serve as a research advisor, but also a mentor. This course often times provides the students their first opportunity to work directly with their research mentor. Because of that, the mentor has an even level higher responsibility. Research mentors and advisors fulfill a key function in professional development [1]. Research mentors are critically important to career development and professional success. Mentors are those who are willing and able to share their experience and expertise. They reflect on their successes and failures, and can explain what they have learned. Mentors are also interested in the professional development and career advancement of those they mentor. Stephanie highlights that a good mentor needs to have high standards, and expectations. They should be willing to expend time and effort to provide relevant guidance, should be open minded and appreciate diversity [1].

Students often do not realize the difference between qualitative and quantitative research. Traditional students, coming right after undergraduate school or lacking systems engineering experience, sometimes expect to see a tangible product as a result of any research. In this course, they are taught that research can be conducted both qualitatively and quantitatively. Johnson and Onwuegbuzie have reviewed the commonalities between qualitative and quantitative research [2, 3]. Newman shares the idea that the underlying processes for qualitative and quantitative research are similar. Peter Reason and Hilary Bradbury argue that action research is creating knowledge but critically studying (qualitatively) what is in front of us can also help us seek insight into the subject of interest [4]. A systems engineering research study includes investigation of problem, goals, functions, and constraints. The researcher then generates strategies for converting vague goals into specific properties or behavior. The next step is to understand the priorities and ranges of satisfaction. As an engineering manager, systems engineers generate strategies for allocating requirements among the system and the various agents of its environment. Estimating cost, risk and schedule is part of the planning process [5]. It is important to help the systems engineering students understand that research, as the name implies, although detailed and through, does not necessarily entail a long drawn process. Given the semester timeline constraint, all students are asked to finish their research work within 3-4 months. This includes defining the problem, performing the literature review, gathering data, doing the analysis, analyzing the results, and inferring conclusions. Students are encouraged to write about their findings as they do the research.

The system development workshop course is organized around discussion of work related to projects. Lectures are given in areas common to all projects, and in which students may need further instruction. Students are required to provide biweekly updates on their progress. Students are also asked to comment and provide feedback on projects other than their own in the class. The class period serves as a platform to exchange ideas and information on the projects among the course participants.

2. Learning to do Research in Systems Engineering (SYE)

The first challenge that students face is deciding a topic to do research on. In this course, several past student project topics are presented to the students for review. Although students can not repeat a previously completed project, having a list of previous research topics helps them think of the possible ideas for research topics. It also gives them a certain level of confidence in their choice. After choosing a research topic, students are asked to write a brief proposal. In the proposal they are asked to describe the problem to be studied, and outline a plan of study. Students are also asked to present their idea in front of the rest of the class. All the students are encouraged to ask questions and give feedback. The instructor and student feedback early on in this process helps the authors fine tune their research scope and direction.

Students are encouraged to explore the guide for writing proposals. They are taught how to search for articles online and in print. In the recent years, because of digital revolution, a large majority of scholarly articles can be acquired electronically, which makes it rather easy to search for them. Students are asked to justify solving the problem by giving a motivation statement. At the initial stage, students are asked to come up with a skeleton or an outline for their paper, which they later fill in as they get more information. Students are asked to collect references for all the work collected along the way. The iterative research strategy is shown in Fig 1. Following is a research guideline that students are asked to follow.

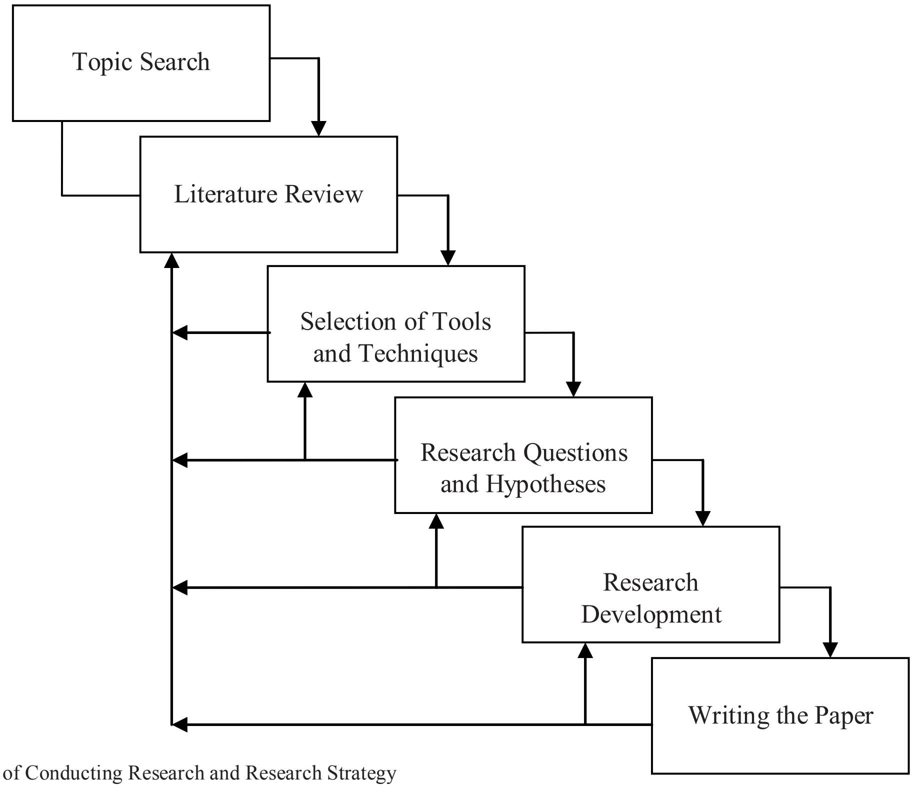

Fig 1: Steps of Conducting Research and Research Strategy

Students are encouraged to ask the Heilmeier questions and ensure that these questions are answered while starting their research [6]. A synopsis of these questions is shown in Table 1. This process is depicted in Fig 2.

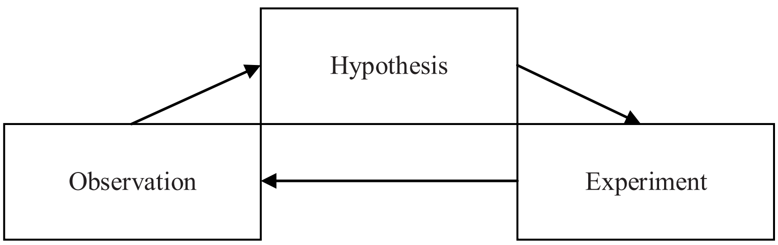

Fig 2: The iterative scientific method

A scientific method is a sequence of procedures intended to discover the truth and separate it from lies and delusions. The tools used are different in different fields but follow the basic framework of defining the problems, forming a hypothesis, testing the hypothesis through experiments, interpreting the results, making a conclusion, and modifying the hypothesis if needed.

Table 1. Heilmeier Catechism

Research Questions
• What is the problem to be addressed? o What motivates interest? Why is it hard? Why is it important? • How is it done today, by whom, and what is wrong with it? • How do you propose to address it? o What's the new idea here, and why can we succeed now but not before? o What recent breakthroughs now make this possible? • What is the impact if successful? o Who cares and what is the quantified value if successful? • What is your plan and approach? o How will the program be organized? o What are the biggest challenges and why? • How long will it take? Why? • What are the milestones? o How will you measure progress? • What investment resources are needed and what is your plan to secure them? o Computational Resources? Facilities? Space? People? Equipment? Management Support? Buy-in?

Heilmeier referred to these questions as 'Heilmeier Catechism.' These questions provide a high level guidance for what information a proposal should provide. The research work results in original creation. It involves investigation and follows a scientific process. In addition to being an informative document, the research paper should be written to persuade the reader. The research is done independently in this course. Students can take initiative and should be able to learn by themselves. The advisor gives advice but does not assign individual tasks to all students. Research requires a strong work ethic, dedication, effort, honesty, self-questioning, and curiosity. In addition to the questions listed in Table 1, students are encouraged to answer the following questions:

- What characterizes the scientific method?
- How exactly does research relate to the scientific method?
- What is a scholarly approach?
- How does one know that a subject meets the requirements of originality?
  - Does the subject go "beyond the undergraduate level"?
  - Will it provide "substantial addition to knowledge"?
- How to do research in an organized and systematic way?
- What should the researcher persuade the reader of?
- How would the researcher improve their work ethic?

It is important to answer these questions for any individual project. Students need to address these for themselves and for communicating to others what they hope to accomplish. The research steps are further explained as follows.

2.1. Topic Search

It is often a good idea to start with intersections of fields of interest. Students are asked to look for problems that other systems engineers will understand and appreciate for example, guide for conducting requirements engineering etc. Students should then look for 'grand challenge' announcements and workshops to learn more about the subject matter. They are encouraged to do high level reading in public periodicals. After doing some preliminary thinking, they are asked to refine the concept in a 30-second 'elevator pitch' to check for clarity and grasp of topics. One of the ways to check whether they understand the problem is to ask them to simplify the statement such that an unknowledgeable person can understand the problem. This pitch is therefore at a high level and should be stamped in their brain [7].

2.2. Literature Review

One of the main tasks while conducting literature review is to define the 'volume' of the research. Although the systems engineering is still in its relative infancy, there is already plethora of research material available in its various subspecialties. Focusing on literature review is particularly helpful because it helps students explore the region of work or areas of fields that particularly pertain to the area of their own interest. Students are encouraged to use published work to discover the community of practitioners. The literature review includes paper references, institutional publications, dissertations, conference proceedings, and journal articles etc. [8].

2.3. Selection of Tools and Techniques

Students are asked to review and explore the various tools and techniques they have learnt from their undergraduate and graduate curriculum. They are taught to be able to defend the choice of techniques and methods for the technical approach. After a set of techniques has been identified, they often use a methodical and structured down-selection technique such as morphological matrix approach. At this point, students start to look at process behind the problem. They identify alternatives for each step. They are prepared to defend selection of alternatives in building their procedure. They are taught to view thesis as an argument or an intellectual position.

2.4. Research Questions and Hypotheses

Research questions and hypotheses have different levels of abstraction and thus they should be presented in a document at the appropriate level. Students are asked to categorize the research questions and tackle them in groups. Hypotheses are guesses of if→ then structures. Based on the prior knowledge gained, students are asked to use scientific process to attack or defend hypotheses (as in P, Q, and P>Q).

2.5. Research Development

It is important for the students to appreciate that design of the process is paramount over results. Students must justify the experiment to validate the answers. It is quite important to setup a 'wind tunnel' for the experimentation of the hypotheses. Designing the correct experiment or sets of experiments is as important as selecting the right topic. If this step is done wrong, the research will not have the necessary substantiation for the work to be approved. At the same time students are taught that running the experiment or building tools is not the end all. Students must sift through the results, find patterns, and look for counter-intuitive trends. Conclusions are highly important area in which effort should be made. Students should include weaknesses they find, future work, ways of improving, alternative methods, and should always relate back to the original research questions and hypotheses [9].

2.6. Writing the Paper

Students are asked to write along the way as they do research as opposed to waiting until the end. Context is important in the 'story-telling' of the report writing process. The executive summary or abstract should be self-contained. One should be able to read and understand fully the motivation, methodology and the import of results. The abstract should be written at the end. The literature review should be tied together into blocks of related thoughts, and to different parts of the logical argument presented. Effective story telling may lead to a good writing. A story has a beginning, body, and an end. Students are taught not to stick it in the background section or in the middle of nowhere. The flow of the paper makes it readable and can often lead to the success. Other sections like introduction, motivation, background etc. should be tuned by definition, while using them to walk the reader from a dead stop to ask questions and then provide sufficient detail to defend the argument.

This research guideline helps to keep the students focused. The intent of the guide is for the students to have a useful educational experience, emphasizing creativity, independent action and learning, research methodology, and scholarly approach. They learn that contribution to knowledge must be original, and should represent substantial addition to the fundamental knowledge in the field or a new or better interpretation of facts already known.

3. SYE Toolbox

A limited set of systems engineering tools that are taught in various SYE classes taught at SPSU are summarized in Table 2. A similar list of tools is available to students taking the research class. After having defined the problem, they are encouraged to employ the tools for their research. There are tools available for each step of the research process. For development of user needs, they can conduct surveys, interviews, or use checklists. For ideas and alternative generation, they can use Delphi Method and Morphological Matrix. For economic analysis they can use time value analysis or rate of return methods. For performance measure they can device 'ilities.' Similarly they can use optimization problems, queuing models, scheduling techniques, logistics models, simulations, forecasting techniques, network models, decision analysis tools, and a number of other tools. A non-comprehensive summary of tools available to students is listed in Table 2.

Table 2. List of Systems Engineering Tools Available to Students

List of Systems Engineering Tools		
System lifecycle definition matrix	Generation of Alternatives	Availability Analysis
Waterfall Model	• Brainstorming	MTBF, MTTR, MTTF, MTBM, MATM
Spiral Model	• Groupware	Optimization
V-Process Model	• Delphi Methods	• Transportation Problem
Evolutionary Process Model	• Morphological Box	• Transshipment Problem
Incremental Development Model	TOPSIS	• Work Assignment Problem
Descriptive and Normative Scenarios	Influence Diagrams	• Shortest Route Problem
System Definition Matrix	Causal Loops	• Line Haul Problem
Input-Output Matrix: Lifecycle phases	Economic Analysis	• Vehicle Routing Problem
Cross Interaction Matrix	• Time Value Analysis	• Traveling Salesman Problem
Objective Tree	• Cost Benefit Analysis	• Maximum Flow Problem
Scorecard Matrix	• Rate of Return Analysis	• Minimum Spanning Tree Problem
Functional Flow Block Diagram	Reliability Analysis	Queuing Models
Quality Function Deployment	State Diagram	Forecasting Techniques
Markov Chain	Simulation	• Judgmental Models
Decision Analysis Tools	Network Models	• Time Series Models
• Decision Tree	• Supply Chain Models	• Causal Methods
• Decision Matrix	• Stochastic Models	Pugh Matrix
• Force Field Analysis	Voting Approaches	Gantt Chart (Bar Chart)
• Grid Analysis	• Plurality	PERT
• Paired Comparison Analysis	• Majority	Precedence Diagram
• Six- Thinking Hats	• Weighted Voting	Ishikawa Diagram
• Pareto Analysis	• Binary Comparison Voting	Work Breakdown Structure
• Intuition	Critical Path Method (CPM)	

4. Sample Student Projects

A sampling of student projects completed over the past five years is listed in Table 3. All of these projects have been completed by students in the Masters of Science degree program as part of their required research projects.

Table 3. Examples of Completed Student Projects

Project Titles
• Data Management and Validation Software Project
• Systems Engineering Approach to First Responder Interoperability
• Implementing Earned Value Management in a previously cost plus contract environment: C-5 Reliability Enhancement & Re-Engining program low rate initial production
• Development of a hybrid water heater using passive heating method
• Global bioburden program for C.R. Bard
• Ruggedized Displays for Aerospace and Military Applications
• Development and Implementation of an Enterprise-Wide SPC system in a manufacturing facility
• Embedded System Design: Merging cultures to solve challenging problems
• A holistic approach to solution development for the department of defense's diminishing manufacturing sources and material shortages (DMSMS) system: design architecture for the 21st century
• Solutions for connecting wind energy sources to the U.S. power grid
• Improving the Drop-off recycling cooperative: Forsyth County
• Home modification for wheelchair accessibility
• Metro Atlanta: Alternatives to traffic congestion Issues
• Systems engineering methodology for managing project requirements
• Tea company reliability study
• Implementation of working cell concept in a process centered environment
• Renewable energy in east Africa: Solutions for providing electricity using a systems approach
• Customer perspectives and their effects on an adaptive supply chain
• Design, development, and implementation of a Quality Management System
• Integrated development strategy from a systems engineering perspective, a case study for anambra state, Nigeria
• Ethanol-Based fuel system: Analysis and design of an alternative to fossil fuel infrastructure in the U.S. motor fleet
• Suniva: Lot tracking and daily reporting issues in MES system
• Causes, consequences, and solutions to water pollution in Africa: Nigeria as a case study
• Converting to Lead-Free PCB in Manufacturing
• Method For Determining Applicability Of A COTS Solution To A Military Aerospace Procurement Contract
• CNS/ATM Integration in Military Aircraft
• Managing Rapid Engineering Programs using Systems Engineering Principles
• Use of SmartPhones For Augmentary Weather Early Warning
• Mobile Lifeline: System Engineering, Analysis, Reporting and Evaluation
• Tools and Techniques to Improve the Input Process to Systems Engineering Requirements Analysis
• A Framework for Cost Savings & Efficiency Improvement in the operation and maintenance of Hornet village residential hall (HV-1) of Southern Polytechnic State University
• Securing Industrial Automation Systems
• The Use of System Engineering Tools and Information Technology for Improvement Within the Healthcare Industry
• Project Automation of Manual Pentachlorophenol Treating Plants
• Revamping Industrial Automation System with Minimum Production Loss

- A System Engineering Approach to LEAN implementation
- Discovering Cloud Computing's Silver Lining for the Federal Government
- Ocean Energy – An Alternative Energy Source
- Application of Systems Engineering to Optimize Famine Relief
- Techniques to increase sales and revenue of a small business
- Preventing and containing oil spills to protect future environmental disasters
- Improving software testing efficiency through the use of modeling, simulation, and risk analysis
- Modern hospital pharmacy – curing medicine distribution with a dose of technology
- Systems engineering tools and Georgia elections – A Precinct case study
- United States Coast Guard (USCG) Inland Construction Tender (WLIC) Reduction Impact on the Marine Transportation

The project topics vary from core systems engineering principles like requirements engineering process improvement to discovering possible solutions to applied projects like comparing the alternatives for traffic problems in the Atlanta area. Students spend approximately 4 months to do the research. They go through the iterative process depicted in Fig 1 and learn to appreciate how research is conducted at the graduate level. Because of taking this research course, a small number of students have indicated their interest in pursuing research beyond what is required for the course. They realize the importance of research. Some also appreciate having contributed to the body of knowledge in systems engineering. Some see it as an evidence of scholarly work that helps them in their professional careers. At least one student has gone on to pursue doctoral research after having taken the research class, writing a high quality research paper and getting it published in a recognized journal [10].

Conclusions

In this paper, the idea of encouraging research projects at the graduate systems engineering program is introduced. Masters level students take a class on research methodologies. They are taught the steps of conducting responsible scientific research and are required to implement those steps along the way to conduct research on a systems engineering related topic. Students are introduced to a few key questions that they are required to answer by the end of the research. This gives them a direction, keeps them engaged and focused. Although the details may vary, the basic steps of conducting a research project follow the same process. Students go through that process in this course. They get a chance to apply the knowledge they have learnt in their systems engineering classes. A toolbox of systems engineering methodologies, tools, and techniques is created and shared with the students. This toolbox is an ever growing list of ideas that students can borrow from to apply to the problems of their interest. Students not only contribute to the database of tools identified in this paper, but they also contribute to the overall systems engineering discipline. The student feedback for this course, which originally started as an experiment, has been positive. Students have indicated that conducting independent research has helped them learn and retain the systems engineering concepts better.

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